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LED bulbs technical specification and testing procedure for solar home systems

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ABSTRACT

The definition of technical specifications and the corresponding laboratory procedures are necessary steps in order to assure the quality of the devices prior to be installed in Solar Home Systems (SHS). To clarify and unify criteria a European project supported the development of the Universal Technical Standard for Solar Home Systems (UTSfSHS). Its principles were to generate simple and affordable technical requirements to be optimized in order to facilitate the implementation of tests with basic and simple laboratory tools even on the same SHS electrification program countries. These requirements cover the main aspects of this type of installations and its lighting chapter was developed based on the most used technology at that time: fluorescent tubes and CFLs. However, with the consolidation of the new LED solid state lighting devices, particular attention is being given to this matter and new procedures are required. In this work we develop a complete set of technical specifications and test procedures that have been designed within the frame of the UTSfSHS, based on an intense review of the scientific and technical publications related to LED lighting and their practical application. They apply to lamp reliability, performance and safety under normal, extreme and abnormal operating conditions as a simple but complete quality meter tool for any LED bulb.

These tests have been applied to a group of 14 low-cost direct current LED bulbs and the accomplishment of the proposed requirements is analyzed.

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Abbreviations: CC, constant current; CFLs, Compact Fluorescent Lamps; EMI, electromagnetic interference; HP, high power; HB, high brightness; IC, integrated circuit; Li-ion, lithium-ion; PCB, printed circuit board; PVRE, photovoltaic rural electrification; SHS, Solar Home System; UTSfSHS, Universal Technical Standard for Solar Home Systems

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1. Introduction

LED lamps have introduced a new way of electric light generation from an electronic source which is overpassing conventional technologies traditional barriers of light efficiency and reliability [1] and have become the optimum solution for solar home systems considering "cost effectiveness and robustness" [2]. For example, the luminous flux of 8-W Compact Fluorescent Lamps (CFLs) is around 400 lm while low/medium class LED bulbs can overpass this value with only 5 W, and is expected to reach soon peak efficacies over 200 lm/W and to reduce their basic cost up to 95% by the year 2030 [3,4].

Moreover, this type of devices are built without any amount of hazardous elements like mercury or lead which is one of "the most imperative features of solar-powered LED lighting" installations [5]. Comparing CFL and LED bulbs on equivalent quality basis with respect to the expected lifetimes, the first ones have, on average, 12 times higher potential environmental impact due to reduced hazardous and rare metals [6] and there are many investigation projects to minimize the usage of hazardous metals in the LED manufacturing process [7]. These bulbs, when broken, must be treated as any other electronic device with no battery such as any small home appliance: preferably repairing them and, when it is not possible, disassembling them and reusing or recycling their different pieces. Many national and local policy and legislation are being created along this basic principle [8].

Concerning the specific area of the Solar Home Systems (SHSs), the off-grid electric lighting solutions have evolved in the last decades from the initial combination of fluorescent lamps and small incandescent ones [9,10] to CFLs [11,12] and finally to LED bulbs that are expected to grow at a very significant rate, especially in developing countries [13]. For example there is an estimation of 40–45% year-on-year growth in Africa through 2015 [14]. There are some particular characteristics that make it very easy to relate the SHSs and the LED lamps. The electronic nature of the semiconductor crystal, which acts as the new light source, works on low DC voltage and can be easily adapted to solar energy generators and batteries. Thus, this make this technology a very promising opportunity in SHS, substituting the current CFLs.

In the past, the quality of SHSs in general, and CFLs in particular, was impelled with the elaboration of many dedicated norms designed by different entities that, in many cases showed important differences in their requirements and specifications [15–24]. In this situation, the collaboration between worldwide experts financed by the EU crystalized in the Universal Technical Standard for Solar Home Systems (UTSfSHS) in order to unify technical and procedure criteria [25]. This norm inspired other specifications like the one of the Bolivian IDTR program [26,27] or the Peruvian PER project [28].

Now it is necessary to adapt the UTSfSHS to the new LED lamps and, consequently, this paper proposes a specific technical specification for this kind of lamps when used in decentralized DC Photovoltaic Rural Electrification (PVRE) applications together with its required quality tests.

The proposed technical specifications and testing procedures have been applied to a representative collection of different models of $12V_{DC}$ LED bulbs acquired in the current SHS market. Results are discussed and they illustrate the relevance of the technical specification proposed in this work and the current state of the art of LED bulb lamps.

2. Review of the current standard for LED lamps technical specifications

As well as with the CFL bulbs as the LED technology is becoming more popular there are appearing several specification lists to ensure the reliability, performance and security for lighting devices based on these electronic circuits. Many of them are generated for general porpoise product [29–33] but there are also several specifically generated for off-grid DC equipment [34-36].

These specifications are based on general lighting technical regulations and on manufacturers and testing laboratories and international agencies recommendations based on the reliability and performance knowledge generated with standard electronic components and that has been used to generate specific test for LED encapsulations. For example, the lifetime of a LED lamp is defined by the Illuminating Engineering Society (IES) in their standards LM-79 and LM-80 and Energy Star has developed the TM-21 procedure guide to foresee the lumen maintenance of the semiconductor crystals over the time along with its current input and working temperature [37]. These proposed tests are long time consuming (LM-80 asks for at least a 6.000 h test for good long term predictions) and require of expensive measurement equipment. Many laboratories in developing countries are not prepared to prepare and realize many of the tests proposed in these specifications lists. Thus, it is necessary to generate a reviewed list of requirements that guarantee the performance of LED lamp on SHS and off-grid installations and that can be revised by local technicians without requiring long periods of time or non-affordable equipment by the capacity of that type of laboratories.

3. Technical specifications

The quality of LED lamps for rural electrification should be judged in terms of its reliability, performance and safety, and so

these categories will be used to present the proposed specifications in the next sections.

In this case we have considered LED bulbs working in a Solar Home System with lead–acid batteries; the most used PV rural application around the world. In the last few years PV rural installations called “Pico Systems” have been developed. They are low power systems (between 1 and 10 Wp) for mobile lighting and mobile charging [38,39]. These systems are designed following the criteria of offering 60 lm – 5 h per day. This value is defined as the minimum lighting requirement by the Sustainable Energy for All Initiative (SE4ALL) launched by the General Secretary of the United Nations [40]. To achieve these performance the required capacity installed is between 0.15 and 110 Ah [41,42], values that are easily obtained with Li-ion batteries. However, these requirements and values are quite lower than the normal requirements for a SHS with an average power installed between 10 and 100 Wp and much higher battery capacity [39]. Lead–acid battery units can offer between 1 and 1400 Ah. [42].

LED bulbs are a massive-production retrofit concept of a conventional incandescent or CFL bulb that can be used on the same luminaries and sockets already present on SHS. They allow a low cost easy evolution to this new LED technology. Fig. 1 shows the basic configuration of a LED bulb lamp detailing their main components.

Following the format of the UTSfSHS [25], the technical specifications have been classified into three groups to consider the required flexibility to be adapted to the different economic circumstances of the countries where decentralized PVRE programs are carried out:

- Compulsory (C): Minimum accepted performance.
- Recommended (R): Good set of working parameters.
- Suggested (S): Maximum performance.

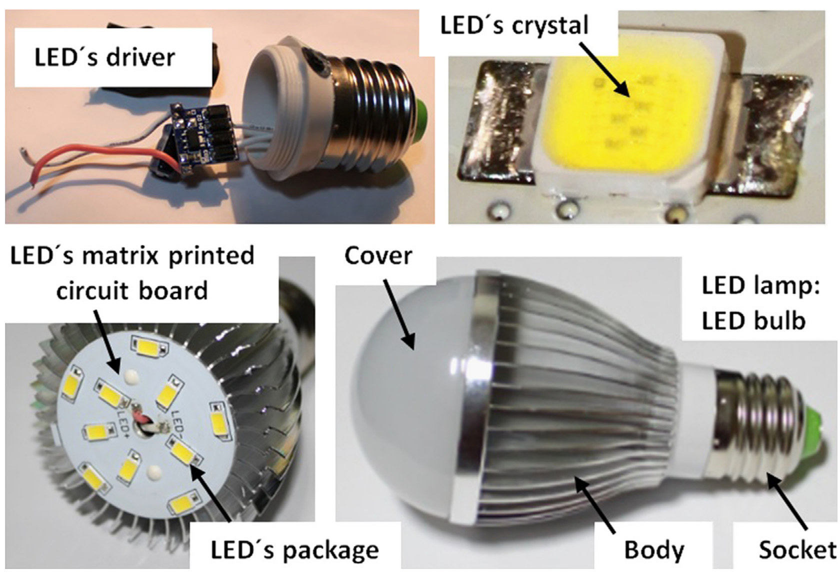

Fig. 1. LED bulb's components description.

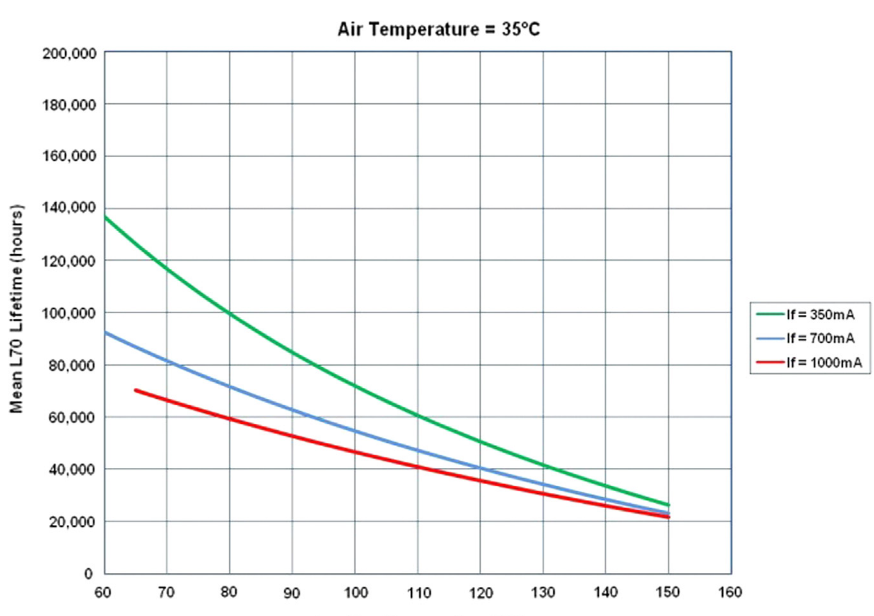

Fig. 2. Example of LED lifetime expectation dependency with semiconductor crystal's working temperature and input current.
Source: Cree [24].

The technical specifications have been proposed taking into account the compatibility with the norms of charge regulator, wiring and battery of the UTSfSHS. In particular, the considered battery is lead–acid as the most common model due to its low cost, simplicity of manufacturing and life cycle considerations [43,44] although the adaptation to Li-ion batteries is not complex, as it will be probably necessary to redefine only the voltage range of the system widen it up to cover the full working range of this technology, and will be the objective of future works.

3.1. Reliability

Special attention is given to reliability as it is the key design factor in rural electrification. On CFLs the main reliability concern is related to the degradation of their electrodes due to usage and turn on/off cycles. However, in LED bulbs, due to the electronic nature of this technology, reliability is highly related with the working temperature. Studies from manufacturers, independent scientific groups and testing laboratories [45–51] show how LED lifetime is dramatically reduced as their working temperature increases. One manufacturer's long term lifetime information of a significant LED present on the market depending on it semiconductor crystal working temperature is shown in Fig. 2.

The first source to check the LED reliability is the information given by the manufacturer about the fulfillment of these standards. So,

- *The bulb's manufacturer must provide the information of the LED's model and manufacturer* (**R**).
- *The LED model used must have a published LM-80 report (IES-LM-80)* (**R**).

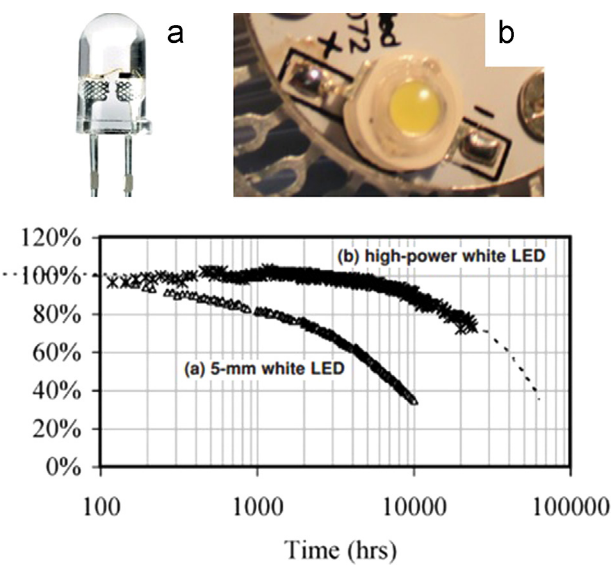

Fig. 3. Comparison of LED's long term lifetime expectation depending on the type of LED package and their construction methodology.

The working temperature of the semiconductor crystals is very difficult to measure due to their covers and packages. However, this value can be estimated according to the temperature measurement of the LED matrix's printed circuit board (PCB) and using average thermal resistance values depending on the type of the different models of LED packages. These values range from 5 to 10 °C/W for High Power (HP) lighting classified LED (0.5 W or higher nominal power single devices with dedicated or independent thermal relief pad underneath the package) to values over 50 °C/W proper of High Brightness (HB) displays application devices. The worst case is found in the 5 mm epoxy through-hole packages where the thermal resistance achieves the highest values. Many different studies such as the one from Nerendan et al. [52] show how the estimated lifetime expectation of these two different types of LED packages offer completely different lifetime performance as detailed in Fig. 3.

Consequently:

- *No full epoxy LED package must be used on the bulb's LED matrixes* (***C***).

Internal LED temperatures around 85 °C in bulbs with specific lighting HP LED packages conduct to temperature values on the PCB between 65 and 75 °C. However, with HB LEDs the expected temperature value are around 45–55 °C [53]. If the measure taken is below these values it indicates that the heat may not be properly evacuated from inside the LED's crystals. If the measure is over that ranges the semiconductor crystal is most probably over 85 °C and the reliability of the lamp is compromised [54–56]. So,

- The LED matrix's temperature nearby the LEDs must be between 65 and 75 °C for High Power LEDs and between 45 and 55 °C for High Brightness LEDs at nominal voltage and 25 °C of ambient temperature (**C**).

The Integrated Circuits (ICs), the inductors and electrolytic capacitors of the LEDs drivers are thermal dependent on their lifetime expectancy and on their working behavior. Their temperature must be always under their absolute maximum rating, so that no catastrophic failures are expected.

To guarantee a good thermal evacuation from the bulbs, they must have the necessary elements to conduct the heat from the LED packages to the surrounding air. To minimize energy consumption the generalized solution is to use its main body as a heat sink so that a natural convection process cools the bulbs [57].

In the market they can be found two main body designs as presented in Fig. 4:

- Plastic bodies: They avoid direct contact with the electronic components and the heat evacuation from the driver is based on some holes in the body as they have a very low heat dissipation capacity.

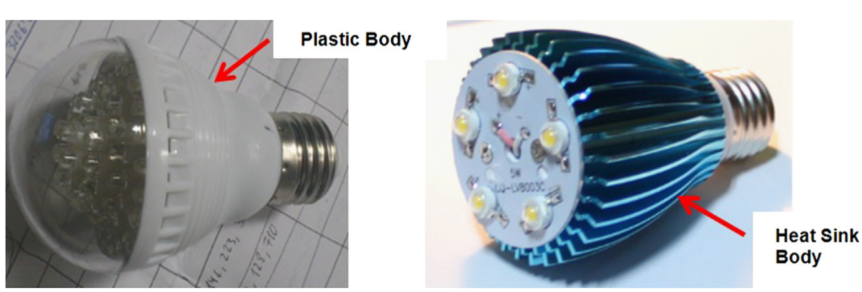

Fig. 4. Bulb's LED matrixes: (left) 5 mm epoxy through-hole packages and plastic case (right) SMD thermal PAD high power LED package and metallic heat sink.

- Metallic or ceramic bodies: These materials have a high thermal power transmission capability. The heat from the LED is evacuated by direct conduction and the complete system is cooled by the ambient air.

Thus, in order to guarantee high long term lifetime reliability:

- The bulb must have a metallic or ceramic heat sink (**R**).

The temperature of the heat sink should not be below 45 °C (at 25 °C ambient temperature) as it would show that there is not a good heat evacuation channel on the bulbs and all the energy is kept on the semiconductor crystal or in the integrated circuits [58]. So,

- *Bulb's heat sink temperature must be at least 20 °C higher than the ambient temperature with the LED bulb working at its nominal power* (**C**).
- *The temperature of the heat sink must not be over 70 °C (at 25 °C ambient temperature) to avoid overheating in the LED's electronic driver* (**C**).

To complete an exhaustive thermal reliability analysis, it is necessary to disassemble the bulb to identify all the ICs, inductors, and electrolytic capacitors required by the LED drivers (as shown in Fig. 1). Their technical documentation will give some initial basic information about their reliability and lifetime estimation. So, it will be required:

- *All the electronic components of the bulb's LED driver must have a temperature maximum rating of 85 °C or higher* (**C**).
- *All the electronic components of the bulb's LED driver must have a temperature maximum rating of 105 °C or higher* (**S**).

These electronic components must be properly isolated from the heat sink for electrical safety reasons but they also should allow a good heat evacuation to guarantee reliability [59]. There are some non-expensive solutions (such as self-vulcanizing rubber cover) but some high performance materials improve bulb's driver cooling (for example polyimide film cover). So,

- *The electronic driver must be properly isolated from the heat sink of the bulb with a specific protection cover* (**C**).
- *The electronic driver must be properly isolated from the heat sink of the bulb with a specific protection cover with high heat transfer properties* (**R**).

As indicated, optimum heat dissipation is generated by a conduction process from the LED to the surface of the lamp where this energy is finally extracted through non-force convection to the open ambient air. This contact channel needs to be well finished so that heat can flow properly. Manufacturing errors such as bad assembly unions (like the one shown on Fig. 5) can generate high lifetime reductions and, in some cases, fatal failures [56]. So,

- *No visible manufacturing assembly failures on heat transfer elements are allowed* (**C**).

Furthermore, if the thermal pad underneath the package of the LED is not properly solder, the heat generated inside the LED bulb has not an optimal solid path to be evacuated [56]. This is easily observed with a thermal camera but hard to observe otherwise. In this case we recommend trying to solder out the components though their anode and cathode accessible pins. If the underneath pad is properly solder with solder past and a reflow oven it will be impossible to move away the LED.

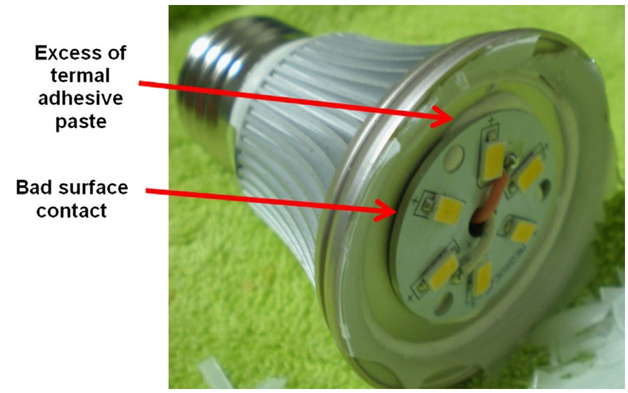

Fig. 5. Example of bad contact assembly procedure of a LED PCB with the bulb heat sink.

- All the PADs of the LED's packages must be properly soldered (**C**).

As these previous standard tests analyze just the different components of the LED bulb and not the reliability of the complete bulb equipment [60], the LED bulb will have to fulfill the following specification.

- LED bulbs must maintain at least 90% of initial light output after 1000 h of a continuous turn on status at nominal voltage and $Ta = 25$ °C (**C**).

3.2. Performance

The electrical performance of LED bulbs should be evaluated according to their efficiency and to a good match between their electrical characteristics and the SHS requirements.

Regarding their electrical characteristics, it is a common practice to advertise the LED bulbs with the direct diode's nominal power used in the devices (i.e. five 1 W LEDs → 5 W bulb) and they do not take into account the electrical losses of the drivers and the input electronic protections. A large difference between these two values can lead to a bad sizing of the elements of a SHSs. So,

- *The LED bulb's real power consumption must be within a 10% tolerance range around its nominal value* (*at nominal voltage and 25 °C of ambient temperature*) (**C**).
- *The LED bulb's real power consumption must be within a 5% tolerance range around its nominal value* (*at nominal voltage and 25 °C of ambient temperature*) (**R**).

Furthermore, many 12 V bulbs of the market are designed to be used both on DC or AC input voltage. Thus they are rather thought for some grid-connected homes with a 12 V transformer rather than for an off-grid SHS with batteries, and they cannot work at the complete range of operating values specified by the UTSfSHS [25]. Thus, considering the voltage range for a lead–acid battery:

- *The LED bulb must not show any misperformance in the voltage range from −15% to +25% of the SHS nominal voltage at 25 °C of ambient temperature* (**C**).

Regarding efficiency, the most used comparison parameter is the ratio between the total light output and its power consumed, measured in lumen per watt. Even though this measure does not cover the advantage of the directional nature of the emission of

the LED and their lower dependency with the reflectors of their luminaries [61], we still will keep this ratio as reference.

Based on the state of art and the expected evolution of the high power LED technology [62–65], the LED bulbs efficiency requirements at nominal voltage and 25 °C of ambient temperature should be:

- o *The luminous yield for the total LED bulb system must be ≥60 lm/W* (**C**).
- o *The luminous yield for the total LED bulb system must be ≥80 lm/W* (**R**).
- o *The luminous yield for the total LED bulb system must be ≥100 lm/W* (**S**).

Finally, a correct performance must be assured even in extreme ambient temperatures. So,

- ○ *No light flickering or instability must be present on extreme ambient temperature* (*–10* °C *and 50* °C) (**C**).

3.3. Safety

In order to ensure that the bulb is built under environmental friendly conditions and will respond to the expected parameters of the technology the manufacturer must guarantee that all the components used and the manufacturing substances comply with the WEEE or the RoHS directives [66].

- ○ *The LED bulb's must be certified by the manufacturer to comply with the WEEE or the RoHS directives* (**C**).

The reliability of the equipment depends on their ability to withstand normal and abnormal operation conditions: LED bulbs must assure their own long-term integrity but also the user's safety. The LED bulbs must be designed to avoid the following risky situations:

- ○ The bulb's body must not allow that any electric active element can be touched by persons.
- ○ The LED bulb must have protections against humidity or insect entrance.

It is worth to note that, to improve heat dissipation, many LED bulb designs show many open spaces to easy air flown and so improve LED cooling. These open spaces must not compromise the user's security or allow that insects, dust or other elements may get inside the bulb reducing its functionality or endurance [50].

Because of the design of a bulb with an Edison's socket, active parts are on the outside surface of the device, so all the considerations about protections will be done with the light emitting surface and the main body (plastic or metallic) of the bulbs.

If we consider personal safety on a DC device an equivalent IP20 rate is enough as it covers that a finger (12.5 mm of diameter) cannot touch the bulb driver or the LED matrix [67]. However, the protection against humidity and insects needs of a harder requirement level that will depend on the expected placement of the lamp [68].

- o *The LED bulb's cover and main body must have an equivalent IP protection rate of at least IP22 for indoor usage, or IP43 for outdoor usage* (**C**).
- o *The LED matrix and the driver's electronic components must be covered with a protective coating against moisture, dust, or chemicals* (**R**).

The E27 Edison screw is a common bulb connection system both for AC and DC input power devices. This makes possible to place low voltage DC bulbs on AC networks what implies an important electrical risk in case of wrong usage. So, in accordance with the norms about wiring in the UTSfSHS [25],

- ○ *A durable DC input voltage label must be visible on the bulbs* (**C**).

Furthermore, the devices must be tested to be safe in case of inversion of polarity of the input power.

- o *The LED bulb must be protected against destruction when the supply voltage is reverse-poled* (**C**).
- o *The LED bulb must work if the supply voltage is reverse-poled* (**R**).

The bulb must be able to survive to abnormal working conditions of a SHS installation and/or wrong performance of any other SHS components. This is the case, for example, if the charge regulator allows abnormal voltages on the system close to the solar panel's open circuit values (for a 12 V SHS installation, a 21 V voltage supply) [69]. So,

- ○ *The device must have a safe behavior and do not break over a period of, at least, 30 min, a solar panel's open circuit voltage* (**C**).

Finally, the generation of electromagnetic interference (EMI) on other electronic devices over the air or the electric line must be below certain level so that the user does not perceive any inconvenience when the LED bulbs are turned on [70]. Thus,

The LED bulb must not produce radio frequency interference (**C**).

3.4. List of specifications

As a summary, the complete list of LED bulb's specifications is shown on Table 1. It is worth to underline that this set of specifications has been conceived to be used in contractual frameworks.

4. Quality control procedures

The procedures to check the fulfillment of the LED bulb's technical specifications are described in the following subsections. All these procedures have been designed under the principle of simplicity and affordability, so that they can be applied by local laboratories within the reach of the countries where PVRE programs are carried out, equipped only with the basic electrical instrumentation [71].

All the LED bulbs tested under these procedures must be working under stable conditions. Prior to turn on any LED bulb, both the LED matrix and its driver are at ambient temperature but, as soon as the LEDs start emitting, the temperatures of their crystals raise and so this changes the behavior of the bulb. It requires between 20 and 30 min reaching a stable working state. For this reason all the measures of the following proposed tests must be taken after a pre-heat period of at least 30 min. [72]

4.1. Reliability: working temperature

Many concerns and requirements about the reliability of the bulbs related to their working temperature can be verified with a simple direct visual inspection of the bulb's package, its body and the components placed inside it (CLED5, CLED7, CLED8, RLED3, RLED4 and SLED1).

However, the rest of requirement verifications need of several specific tests. As explained before, direct temperature measurements are hard to obtain and, consequently, to verify: the semiconductor's crystal is usually under a solid case and the electronic driver of the

Table 1
Proposed UTSfSHS's technical requirements for LED bulbs.

Compulsory	
CLED1	No full epoxy LED package must be used on the bulb's LED matrixes.
CLED2	The LED matrix's temperature nearby the LEDs must be between 65 and 75 °C for High Power LEDs and between 45 and 55 °C for High Brightness LEDs at nominal voltage and 25 °C of ambient temperature.
CLED3	Bulb's heat sink temperature must be at least 20 °C higher than the ambient temperature with the LED bulb working at its nominal power.
CLED4	The temperature of the heat sink must not be over 70 °C (at 25 °C ambient temperature) to avoid overheating in the LED's electronic driver.
CLED5	All the electronic components of the bulb's LED driver must have a temperature maximum rating of 85 °C or higher.
CLED6	The electronic driver must be properly isolated from the heat sink of the bulb with a specific protection cover.
CLED7	No visible manufacturing assembly failures on heat transfer elements are allowed.
CLED8	All the PADs of the LED's packages must be properly soldered.
CLED9	LED bulbs must maintain at least 90% of initial light output after 1000 h of a continuous turn on status at nominal voltage and Ta=25 °C.
CLED10	The LED bulb's real power consumption must be within a 10% tolerance range around its nominal value (at nominal voltage and 25 °C of ambient temperature).
CLED11	The LED bulb must not show any misperformance in the voltage range from -15% to $+25\%$ of the SHS nominal voltage at 25 °C of ambient temperature.
CLED12	The luminous yield for the total LED bulb system must be ≥ 60 lm/W.
CLED13	No light flickering or instability must be present on extreme ambient temperature (-10 °C and 50 °C).
CLED14	The LED bulb's must be certified by the manufacturer to comply with the WEEE or the RoHS directives.
CLED15	The LED bulb's cover and main body must have an equivalent IP protection rate of at least IP22 for indoor usage, or IP43 for outdoor usage.
CLED16	A durable DC input voltage label must be visible on the bulbs.
CLED17	The LED bulb must be protected against destruction when the supply voltage is reverse-poled.
CLED18	The device must have a safe behavior and do not break over a period of, at least, 30 min, a solar panel's open circuit voltage.
CLED19	The LED bulb must not produce radio frequency interference.
Recommended	
RLED1	The bulb's manufacturer must provide the information of the LED's model and manufacturer.
RLED2	The LED model used must have published a LM-80 report (IES-LM-80).
RLED3	The bulb must have a metallic or ceramic heat sink.
RLED4	The electronic driver must be properly isolated from the heat sink of the bulb with a specific protection cover with high heat transfer properties.
RLED5	The LED bulb's real power consumption must be within a 5% tolerance range around its nominal value (at nominal voltage and 25 °C of ambient temperature).
RLED6	The luminous yield for the total LED bulb system must be ≥ 80 lm/W.
RLED7	The LED matrix and the driver's electronic components must be covered with a protective coating against moisture, dust, or chemicals.
RLED8	The LED bulb must work if the supply voltage is reverse-poled.
Suggested	
SLED1	All the electronic components of the bulb's LED driver must have a temperature maximum rating of 105 °C or higher.
SLED2	The luminous yield for the total LED bulb system must be ≥ 100 lm/W.

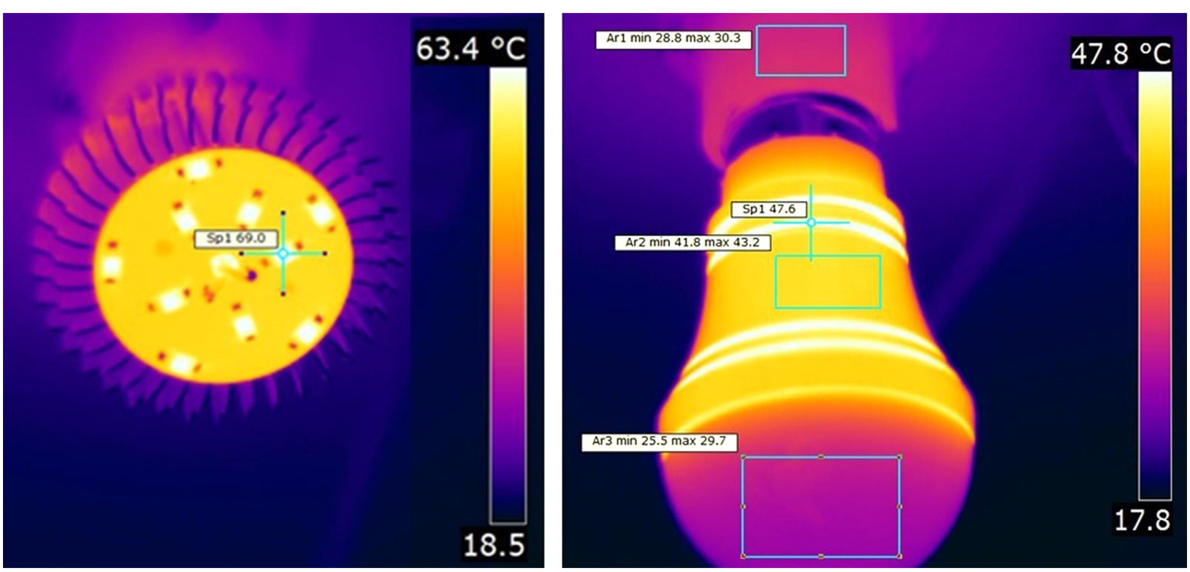

Fig. 6. LED's matrix and heat sink temperature measurement with thermal camera.

lamp in the majority of the cases is not easily accessible. However, some measures of the bulb's PCBs and the heat sinks offer a significant approximation of this value.

Based on the practice, these values can be measured either with a thermal imaging camera or with a cheaper physical contact sensor that allow checking if these temperatures are within the margin specified by the corresponding technical specifications (CLED2–CLED4). Two thermal example pictures from LED bulbs are shown in Fig. 6.

4.2. Performance

4.2.1. Power consumption

The power consumption (CLED10) is calculated powering on the LED lamp at its nominal bulb's input voltage and at 25 °C ambient measuring the current used by the lighting device. This can be measured with an independent electric meter device or a calibrated variable power supply with an electric current indicator. This same test set is used to measure the current required and the

performance of the bulbs in all the battery working voltage range (CLED11).

4.2.2. Extreme ambient conditions

It is necessary to evaluate the behavior of the bulb (CLED13) as a complete end device on extreme cold and warm situations: 5 °C, −10 °C and 50 °C. All the thermal test measures must be done without any forced ventilation system that may be acting over the LED so that the heat sink of the LED lamp works on the same ambient conditions it would have in a common indoor placement without a forced convection help. It is necessary to check:

- The switch-on process.
- Its working stability.
- Any significant changes on their behavior from nominal situations.

As cold ambient temperature allows better light efficiency and lumen maintenance, it is only necessary to analyze the startup process of the electronic driver along all the battery voltage working range (for $12V_{DC}$ systems: $10–15V_{DC}$ in a 1 V step discretization). In the warm temperature case, the switch-on power and the working stability must be checked. Furthermore, both on warm and cold cases, the LED bulb must not suffer any irreversible damage. Thus, after working at such temperatures during 1 h, the correct operation at 25 °C must be checked again.

We have used a climatic chamber that can be configured to work on the three specified ambient temperature. However it is possible to obtain similar results using a conventional fridge with freezer chamber and an oven with temperature regulators.

4.2.3. Efficiency

To calculate precisely the luminance output value (CLED12, RLED6 y SLED2), complex equipment are required such as:

- An integration sphere: That allow to find the lumens emitted by the lamp.
- A goniophotometer: That gives also the radiation diagram of the tested lamp.

These two systems are expensive and fragile equipment and hard to find in the countries where PVRE programs are developed. Thus, we pretend to find out a simple and inexpensive system to obtain a good approximated value of this parameter.

A wide set of LED bulbs have been tested with a goniophotometer that belongs to the University of Malaga (UMA) [73] and we have calculated all their irradiance diagrams. This data has helped us to consider that most of the LED bulbs correspond to two main types of radiation pattern:

- Lambertian: with a sphere-type light emitting pattern that covers a range of approximately 120° from its vertical axis. This type of shape belongs to the “snowcone” shape bulbs. Depending on the type of lamp cover (transparent or diffused) they have no emission on the north hemisphere or a small amount due to reflection respectively (one significant example of a Lambertian bulb aspect and its emission diagram example is presented in Fig. 7).
- Toroid: with a solid interior. This shape belongs to candle and corn cob bulbs (one example of a Toroid bulb aspect and its emission diagram is presented in Fig. 8).

To calculate the real lumens being emitted by the bulbs without using and integration sphere or a goniophotometer, we have used the same measurement equipment than the one proposed by Egido et al. [71]. This is a black box with the following main elements (its general aspect and schematic is presented in Fig. 9):

- 2 centered and symmetric bulb socket for a reference and a testing bulb.
- 2 mobile covers to isolate each of the lamps paced on the box.
- A lux meter placed at its bottom side that can be moved along a calibrated track on the base of the box.

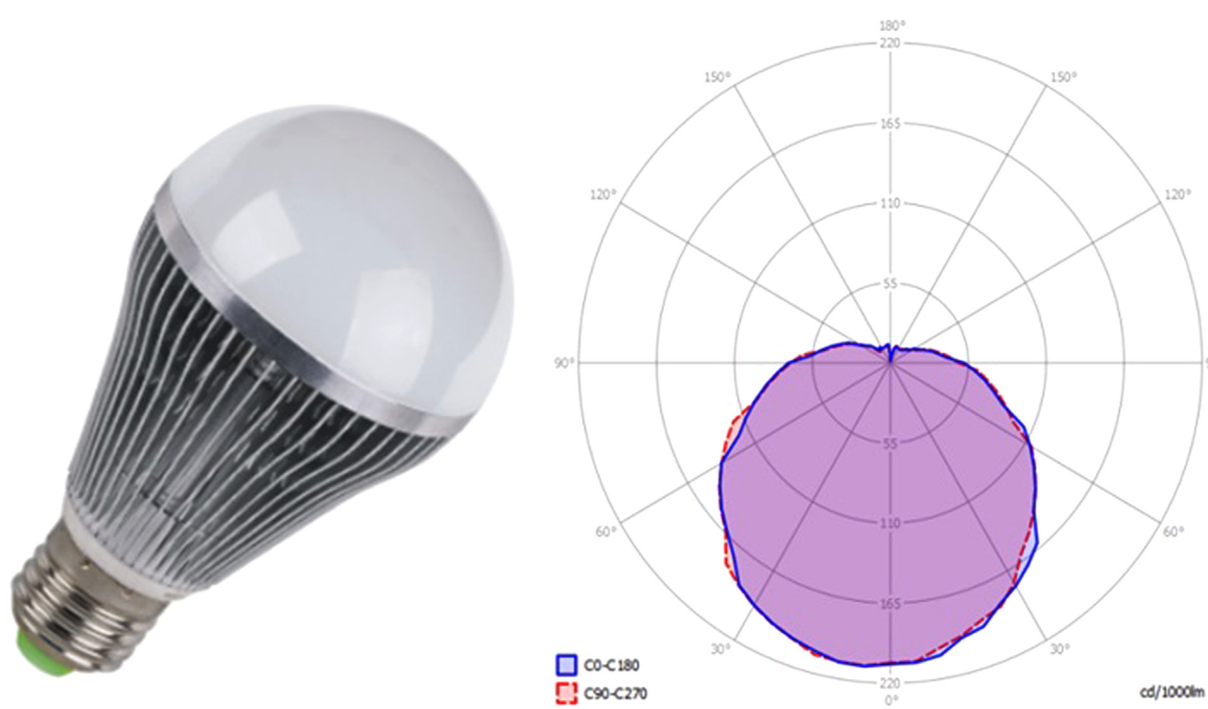

Fig. 7. Snowcone led bulbs and its associated typical lambertian radiation pattern.

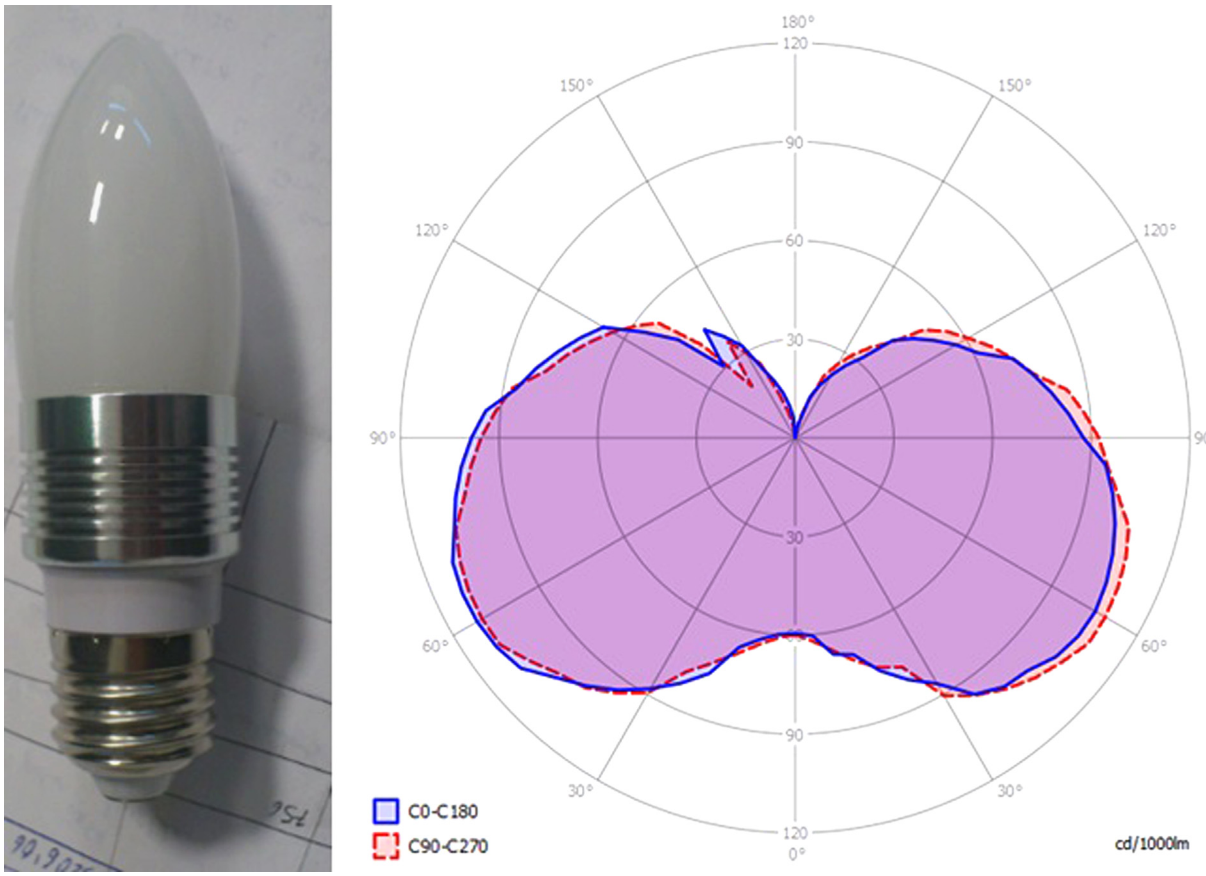

Fig. 8. Candle and corn cob bulbs and their associated typical toroid radiation pattern.

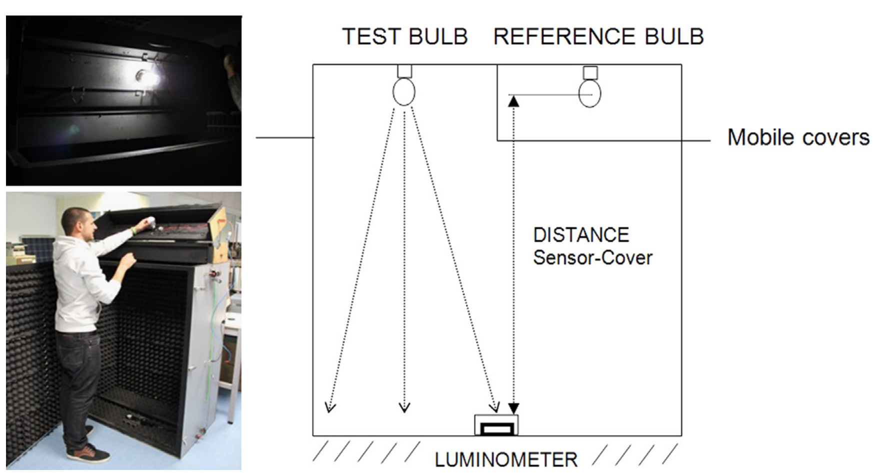

Fig. 9. Black box luminance test device and its schematic diagram.

The box height must be greater than 10 times the size of the bulbs so that they can be considered from the measurement device as a single point emitter [71].

Taking several measures along the longitudinal axis of the box's base looking for the maximum lux value allows finding the radiation pattern of a tested LED lamp and to select the appropriate LED bulb reference. Comparing the illuminance obtained with the black box and the previously known lumens of the chosen reference bulb, it is possible to approximate the lumens emitted by the tested bulb. This value is calculated based on a linear relationship between the highest value of lux measured and the lumens of the tested bulb and its reference.

$$\frac{\text{Maximum normalized luxs (test bulb)}}{\text{Maximum normalized luxes (reference bulb)}} = \frac{\text{Lumens (test bulb)}}{\text{Lumens (reference bulb)}} \tag{1}$$

As expressed on the previous formula, the maximum lux values used must be normalized depending on the different sizes of the bulb's bodies and, consequently, on the different distances sensor-bulb cover.

$$\frac{\text{Luxs}}{\text{Normalized luxs}} = \frac{(\text{DISTANCE sensor} - \text{bulb cover})^2}{(\text{DISTANCE sensor} - \text{bulb socket})^2} \tag{2}$$

It can be observed in Table 4 of Section 4, that the maximum error of this method when compared with the goniophotometer measurement is just 5%.

4.3. Safety

As well as with the working temperature requirements, some specifications can be visually checked (CLED6, CLED14 and RLED7). Furthermore, to verify a good protection for human safety and against humidity and insect entrance (CLED15), the bulbs can be tested as follow:

- Indoor (IP22 equivalent): Placing drops of water and allowing the displacement by gravity along the light emitting zone cover and the main body. After the test the bulb's surface is dried with a mop and then disassembled. No water can be found inside [67].
- Outdoor (IP43 equivalent): Water is sprayed with a diffuser along all the surface of the light emitting zone cover and the main body. After the test the bulb's surface is dried with a mop and then disassembled. No water can be found inside [67].

Furthermore, the devices must be tested to be safe in case of inversion of the power polarization (CLED17 and RLED8). The bulbs must be powered with the two possible polarity combinations given by the E27 screw, and see if the bulbs bright normally on both cases and if in the wrong polarity case, the lamp simply does not turn on or it suffers some type of damage: overheating, capacitors destruction.

Moreover, to check the protection against solar panel open-circuit voltage (CLED18), the bulbs must be powered with an abnormal 21 V input for a period of 30 min [69]. It is necessary to measure the input current values in order to evaluate the power consumed. The bulb may consume a close to nominal power or increase this value. In this second case, after the time indicated on the test the bulb must have a proper functionality on normal input voltage conditions.

Finally, the lighting equipment must not interfere with any other appliance of the house (CLED19). A very simple procedure to test this feature is to use a commercial radio playing a regular emission on the two extreme regions and in the middle of the wavelength radio reception range. The radio will be powered initially with the same SHS line than the bulb and secondly with independent batteries. There must be no perceptible interference on the radio emission placed either very close to the lamps (within less than a meter), and also with a 2 m and a 5 m distance from each other [25].

5. Application to the quality control of 14 representative LED lamp models of the current market.

A set of 14 units of LED bulb from different manufactures have been analyzed according to the tests and specifications presented. The prescriptions used to choose the devices to be tested are:

- Nominal power: between 3 and 5 W.
- Input voltage: $12V_{DC}$.
- Socket system: E27 (Edison screw).
- Low individual cost: < 10 $US (1 unit sample price).

At least 5 units of each model are needed in order to be fully analyzed as several test procedures may finish with the destruction of the bulb. Their main characteristics are summarized in Table 2.

5.1. Reliability

The documentation offered by the manufacturers of our selected bulbs is limited to basic electric information printed on their selling box and some technical specifications listed on the web page of the manufacturer: color temperature, power and voltage input range. However, little more information further than this is available.

Table 2
Description of the bulbs used in this test procedure.

	Lamp model – $12V_{DC}$													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Nominal power (W)	3.0	3.0	3.0	3.0	3.0	5.0	3.0	3.0	5.0	3.0	3.0	5.0	5.0	3.0
Cost (1 unit $US)	2.10	3.60	2.90	3.90	3.20	6.30	4.10	3.10	7.40	3.70	3.60	4.65	4.50	7.50

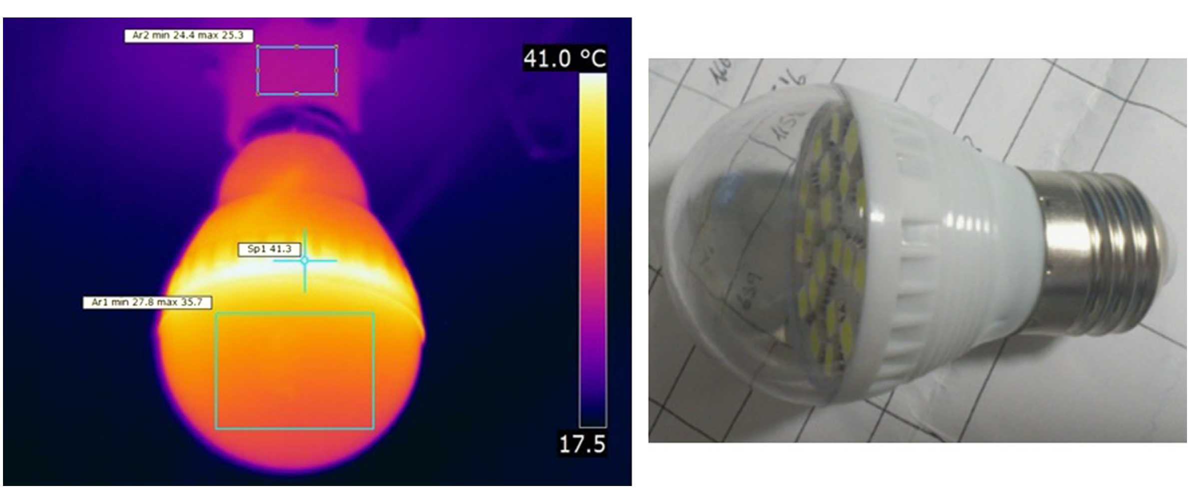

Fig. 10. Thermal image (left) of a lamp with a bad plastic heat sink (right), generating poor heat dissipation from the LEDs.

All of them have a similar structure of screw and cover that can be easily disassembly without special tools so that the LED's matrix and its driver (with all their components) can be analyzed individually.

All the electronic components found are standard and can be easily identified by the references marked on their packages. Their data sheets with their nominal and absolute maximum rated working parameters, temperature ranges and long term lifetime analysis have been found on the internet. All the component's temperature specifications have been analyzed and are adequate to the working range of low power LED bulbs.

A thermograph camera (Fluke Ti25) has been used to check their temperatures. The results are that just one lamp (model 6) failed in CLED2 and lamps models 1 and 3 failed CLED3. All of the lamps fulfilled CLED4.

Note that all the LED bulbs are driven on constant current (CC) and are low power devices, so the heat generated on them is not excessive and is kept under control by the electronic driver. The exceptions are found on two bad heat transfer bodies made with plastic (RLED4), the temperature measure of one of these bulbs is shown in Fig. 10 (where the temperature of its body barely reach 40 °C), and with manufacturing failures as bad thermal pad soldering (CLED8). In Fig. 11 we show a bulb where one LED with this solder problem has a higher temperature than the rest of the diodes.

Finally, LED bulbs have been tested turned on during a 1.000 h period and the maximum lux value has been registered before and after the process. The illuminance depreciation measured (according to CLED9) is shown in Fig. 12.

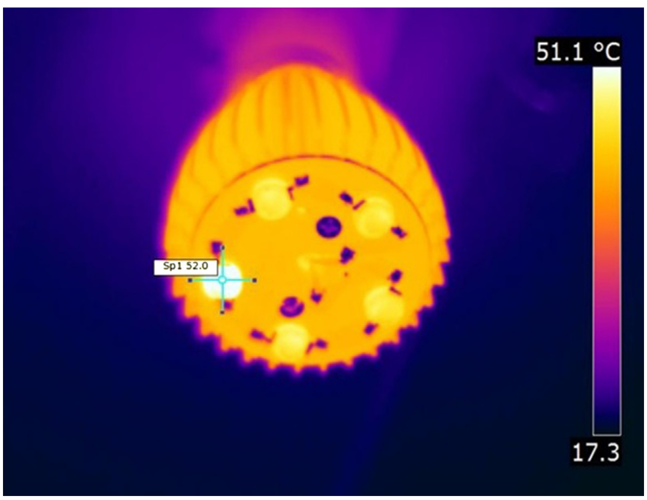

Fig. 11. LED assembly error implies very high individual component's temperatures.

5.2. Performance

The input power of the bulbs has been measured for the nominal $12V_{DC}$ setup after a 30 min preheat process and these values have been compared with the reference given by their manufacturers. The deviations founds are summarized in Fig. 13. 13 out of 14 bulbs consume more than their nominal values, and in eight cases, more than the allowed by the proposed technical specifications.

The behavior with a 10 and $15V_{DC}$ input voltage is summarized on Table 3. The electronic drivers on all the lamps focus on generating a CC for the LEDs with a variable input power range. On many of the 3 W bulbs the drivers do not manage to generate the nominal current of the LEDs on low input voltages and the power and the luminance falls down. Moreover, one electronic drivers could not handle properly a 15 V input and this bulb started to flash and other bulb have the same problem but with a 10 V input.

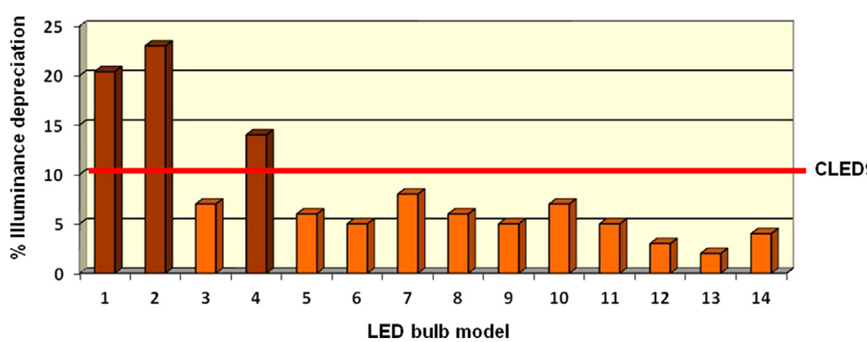

Fig. 12. Bulb's 1000 h light output depreciation results.

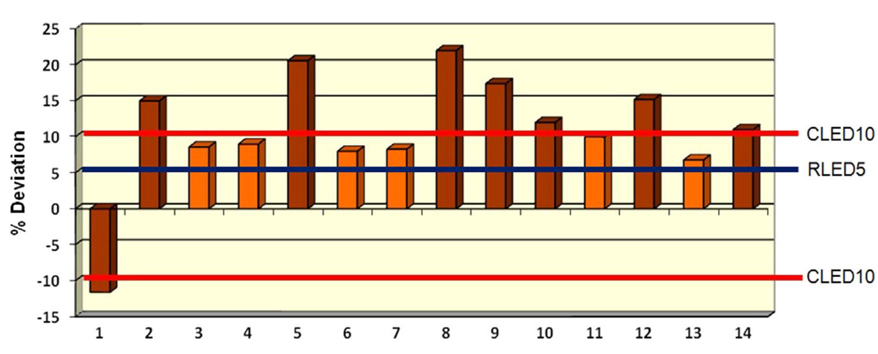

Fig. 13. Deviation of the real power consumption measured from the nominal indicated value.

Table 3
Accomplishment of the requirements related to input voltage range.

Power (W) at	*Lamp model*													
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*
10 V	2.32	1.4	1.52	1.54	1.53	–	1.4	1.65	6.08	1.6	1.05	6.0	5.63	1.4
12 V	2.65	3.45	3.26	3.27	3.62	5.4	3.25	3.66	5.87	3.36	3.3	5.76	5.34	3.33
15 V	2.65	3.24	3.15	3.7	3.59	5.3	3.25	–	5.76	3.3	3.3	5.4	5.14	3.37
CLED11	√	√	√	√	√		√		√	√	√	√	√	√

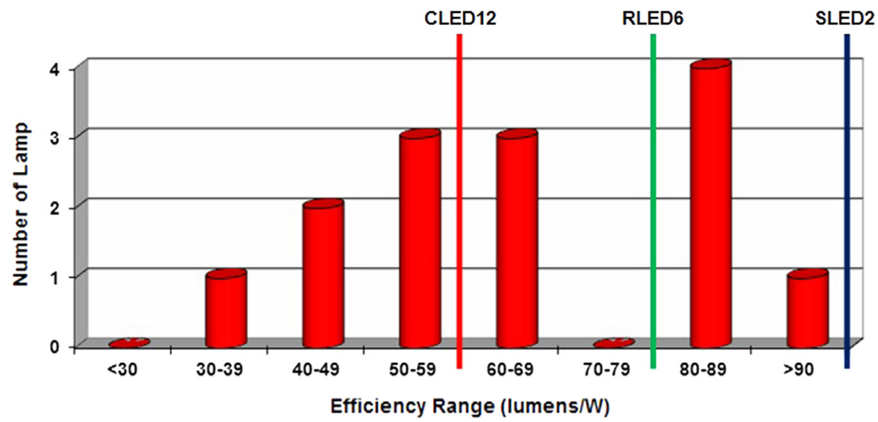

Fig. 14. Bulb's test set efficiency range distribution.

Table 4
Comparison between bulb's lumens calculated and estimated with the black box methodology.

Bulb	**Radiation model**	**Lumens measured (goniophotometer)**	**Lumenes estimated**	**Error (lumens estimated vs measured) (%)**	**Efficiency (lumens measured/W)**
10	Snowcone opal	295	Reference		83
11	Snowcone opal	279	278.706	0.11	90
12	Snowcone opal	473	457.991	3.28	80
13	Snowcone opal	419	431.208	−2.83	88
8	Snowcone opal	274	273.796	0.07	56
6	Snowcone opal	205	213.980	−4.20	51
4	snowcone opal	173	169.191	2.25	51
2	Snowcone opal	166	166.462	−0.28	48
9	Snowcone transparent	282	Reference		36
7	Snowcone transparent	227	217.761	4.24	69
3	Snowcone transparent	213	223.695	−4.78	65
1	Snowcone transparent	271	268.434	0.96	61
5	Toroide – candle	166	Reference		48
14	Toroide – corn cob	214	233.551	−8.37	81

The bulbs have been also tested on the complete voltage working range of 10–15V_{DC} placed inside a HERAES-VÖTSCH GmbH thermal cabinet. The power supply was placed outside the camera that allows measuring the input bulb's voltage and current. The LED bulb tested showed no significant abnormal behaviors rather than the same ones detected on 25 °C ambient temperature tests. The main remarkable aspect is that at 25 °C these two units failed just on the border values of the testing range (10 and 15 V) and with a warmer ambient temperature they failed also within the voltage's range: at 11.5 V (bulb 6) and at 13 V (bulb 8).

Regarding the efficiency test, three different comparison blocks were generated: snowcone with opal cover surface, snowcone with transparent or spotted cover surface and candle – corn cob bulbs. The results are described on Table 4 and in Fig. 14. Just 8 units fulfill the compulsory requirement (CLED12) and only 5 the recommended one (RLED6). The difference between the values obtained with the goniophotometer and those obtained through the lux estimation methodology are in 13 out of 14 bulbs below a 5%.

The main raison to explain the extreme differences between efficiencies measured is the performance offered by the specific LED model used in each bulb. To reinforce this conclusion we have changed the LED matrix of the bulb number 3 (3 W and 65 lm/W output) with a high performance LED matrix PCB: 3 high power CREE MX-6, 4500 °K with a data sheet binning definition of 107 lm (@300 mA & Tj 25 °C with a light output reduction of an 85% @Tj: 85 °C) [74]. The same bulb with this new LED matrix has obtained

Table 5
Summary of compulsory/recommended/suggested requirements accomplished by the LED bulbs tested.

	Lamp model – 12V$_{DC}$													
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*
Reliability														
CLED1		√	√	√	√	√	√	√	√	√	√	√	√	√
CLED2	√	√	√	√	√		√	√	√	√	√	√	√	√
CLED3		√		√	√	√	√	√	√	√	√	√	√	√
CLED4	√	√	√	√	√	√	√	√	√	√	√	√	√	√
CLED5	√	√	√	√	√	√	√	√	√	√	√	√	√	√
CLED7	√	√	√	√	√		√	√	√		√	√	√	√
CLED8	√	√	√	√	√	√	√	√	√	√	√	√	√	√
CLED9		√		√	√	√	√	√	√	√	√	√	√	√
RLED1						√		√	√	√	√	√	√	
RLED2														
RLED3		√		√	√		√	√		√	√	√	√	
RLED4		√		√	√	√	√	√	√	√	√	√	√	
SLED1		√		√	√	√	√	√		√	√	√	√	√
Performance														
CLED10			√	√		√	√				√		√	
CLED11	√	√	√	√	√		√		√	√	√	√	√	√
CLED12	√		√				√			√	√	√	√	√
CLED13	√	√	√	√	√		√		√	√	√	√	√	√
RLED5														
RLED6										√	√	√	√	√
SLED2														
Safety														
CLED6	√	√	√	√	√	√	√	√	√	√	√	√	√	√
CLED14	√	√	√	√	√	√	√	√	√	√	√	√	√	√
CLED15		√		√	√				√	√	√	√	√	√
CLED16	√	√	√	√	√	√	√	√	√	√	√	√	√	√
CLED17	√	√	√	√	√	√	√	√	√	√	√	√	√	√
CLED18	√	√	√	√	√		√	√		√	√	√	√	√
CLED19	√	√	√	√	√	√	√	√	√	√	√	√	√	√
RLED7														
RLED8	√	√	√	√	√	√	√	√	√	√	√	√	√	√

an efficiency measures on the same conditions of 92 lm/W. This is over a 30% efficiency increment just based on the LED selection.

5.3. *Safety*

5.3.1. *Ecological aspects*

All the bulbs are RoHS rated by their manufacturers (CLED14).

5.3.2. *Protections against humidity or insect entrance*

In all the bulbs tested all the drivers were individually isolated. In 5 cases with a basic thermal rubber (CLED6) and in all the other with a thermal transmitter electrically isolated tape (RLED3).

However none of them have neither on the driver's electronic or in the LED matrix a resin protection cover for humidity or dust (RLED7).

Concerning the equivalent IP protection rate either the lamps did not meet the minimum protection (IP22 equivalent) due to holes on their body or pass the highest level prescribed (IP43 equivalent).

5.3.3. *Identification to avoid bad input power AC/DC application*

All the bulbs presented a clear label where it is clearly indicated the nature of the input power voltage (CLED16).

5.3.4. *The devices must be tested to be safe in case of invert power input*

All the bulbs have a diode bridge in the power entrance so that they are not only inverse polarization protected but they are prepared to work independently of the polarization used (CLED17 & RLED8).

5.3.5. *Protection against solar panel open circuit voltage*

Two bulbs (6 and 9) did not regulate properly the input power when applying a 21 V input voltage and thus the input current also increased in a way that the driver broke down after working a few seconds in this mode (CLED18).

5.3.6. *Low EMI generation*

The CC low voltage LED input power of the LEDs requires no power commutation that may generate a significant amount of EMI. The results of all the tests reflected no interaction with the radio emission reception. (CLED19).

5.4. *Summary of results*

Table 5 summarizes all the results of the tests done with the test bulb set to easily verify the new requirement accomplishments of each unit.

Only 2 bulbs accomplished all the compulsory requirements established, although 4 models failed only in 1 compulsory field and 3 more in 2 fields of this segment. Many recommended point were achieved and just one suggested aspect was reached by a few lamps. Most of the failures detected in compulsory requirements are caused by a bad quality non-lighting rated LED and body material choices and inefficiencies in their manufacturing processes.

About the performance requirements, many bulbs do not stand an overvoltage input closed to the shot circuit solar panel voltages, and some drivers do not work properly on extreme ambient temperature.

The main problems with the safety requirements are related to the protection against humidity and insect entrance. Most of the LED bulbs compromise the seal of the electronic components to create some air conduction pipes to improve heat dissipation based on the supposition that these devices will be placed inside a higher protection luminaire [75].

All the measure units and instruments used for the tests proposed can be bought and built for a little less than 1.000€ if the temperatures are measured with contact sensors or infrared sensors with laser targeting devices (that cost around 35€). If a thermograph camera is acquired, the budget raise to about 2.000€.

6. Conclusions

With the new LED lighting devices new possibilities are open for SHS. However, it is necessary to establish the required specifications and tests to evaluate their real quality before using them on the specific operational conditions of real PVRE projects. This is very important in order to guarantee the performance of the devices through the measurement of a list of technical parameters organized on 3 main groups: reliability, performance and safety.

Following the same philosophy of the existing Universal Technical Standard for Solar Home System [25] we have proposed 19 compulsory, 8 recommended and 2 suggested technical specifications and their corresponding quality control procedures for DC LED bulbs using non sophisticated, affordable or own-made measure equipment. These requirements are the result of the combination of a deep review of the many standards existing, the technical specifications of the manufactures of this technology and many scientific publications. This information is contrasted with the compilation of experiences after the evaluation of many SHS PV rural electrification programs with CFLs (and all the problems reported in these installations).

This proposal has been applied to a representative sample of 14 low cost LED bulbs suitable for PV SHS projects in developing countries and the results have been presented. The summary of the test results is that 2 of these LED bulbs comply with all the compulsory specifications and, consequently, would be accepted in a hypothetical process of selection for a PVRE program. On the other hand, it is important to remark that 7 more bulbs tested failed only one (4 models) or two (3 models) of the 18 compulsory requirements and probably could easily pass that fails trough simple corrections.

Moreover, nowadays very few recommended and suggested items are achieved as, in the best case, only half of the recommended requirements are passed. However, LED bulbs are a recent technology and low-cost devices are just starting to appear in the market. It is expected that by the time this work is published many more low cost LED bulbs could easily fulfill all the compulsory requirements and many of the recommended and suggested while prices will be steadily reduced due to massive productions and the consolidation of the technology in the market [76,77].

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